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Evaluation of Currency and Stamp Papers

E. L. Graminski and E. E. Toth

Paper Evaluation Section
Institute for Materials Research

February 20, 1975

Progress report covering the period
July 1 — December 31, 1974

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U. S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary

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1. SUMMARY

1.1 Mechanical Refining, Wet Pressing, and Modification of Paper with Acrylic Resins

The structure of paper affects the durability of paper. Mechanical refining (beating), wet pressing, and the addition of acrylic resins to paper by the beater addition technique have a significant effect on the structure of paper. The relationship between the three aforementioned variables on the durability of paper was determined.

A kraft wood pulp was mechanically refined (beaten) to various degrees and formed into handsheets which were pressed at either low or high pressure. Some of the beaten pulp was modified with acrylic resins known to have varying effects on the structure of paper. One half of each handsheet was flexed on the National Bureau of Standards paper flexer, and the properties of the flexed paper were compared to those of the unflexed portion.

Beating increases wet fiber flexibility resulting in a more compact fiber network structure and a denser sheet. Increasing amounts of wet pressing also compacts the fibers, resulting in greater paper density. The effects of wet pressing are greatest at lower levels of pulp refining. Acrylic resins cause the fibrils and debris to redeposit onto the fibers ensuing in a more porous sheet.

The fines, produced during mechanical refining, form a film-like material (matrix) in the interstices of the fibers during the formation of paper. This matrix serves to restrain the lateral movement and the twisting of fibers when paper is strained, compelling the stresses developed in the fibers to dissipate axially rather than transversely. Stress dissipation in the direction of least resistance is restrained and, consequently, the modulus and stiffness are higher. If the matrix deteriorates when paper is flexed, a significant decline in stiffness and modulus results.

As mechanical refining and wet pressing increases, the free volume of paper decreases precluding lateral movement and/or twisting of fibers, and the matrix contributes less and less to paper stiffness. If there is little or no degradation of interfiber bonding during flexing of dense paper, the free volume does not increase appreciably and the bending stiffness does not decline as extensively as it does in less dense papers.

Modification of paper with certain acrylic resins results in a further improvement of stiffness retention during flexing. The effect of the acrylic resin on the structural changes of paper does not diverge at different levels of mechanical treatment. An analysis of the effect of acrylic resins on the stiffness retention of paper indicates that the acrylic resin should be located at or near the top and bottom surfaces of paper for greatest utility.

Additional work must be done to determine the most effective means for obtaining high density currency paper.

1.2 Modification of Currency Paper

Laboratory results with handsheets indicated significant increases in stiffness retention with flexing would result when paper was modified with certain acrylic resins by the saturation technique. Results obtained from handsheets, however, are not always equivalent to results obtained with machine made paper. Therefore, machine made currency paper was treated with acrylic resin AC-61 to determine if the treatment would also improve its stiffness retention. The reason for choosing resin AC-61 was because it produced the best results in handsheets.

The stiffness retention with flexing of currency paper treated with AC-61 was superior to currency paper normally sized with a glue-glycerin mixture. The results suggest that a mill trial should be conducted in which currency paper would be modified with AC-61 by saturation to enable a full scale evaluation of the acrylic resin treatment.

2. THE EFFECT OF MECHANICAL TREATMENT ON THE STIFFNESS RETENTION OF PAPER WHEN FLEXED

2.1 Background

The mechanical refining of pulp and wet pressing of paper after formation significantly affect the mechanical properties of finished paper [1], as both treatments influence interfiber bonding and fiber strength. The effects of mechanical refining and wet pressing on the structural and mechanical properties of paper and on the stiffness retention of paper with flexing have been evaluated and are reported here.

Previous studies [2-5] on the modification of paper with acrylic resins by beater addition indicated that fibrils and debris redeposited onto the fibers, resulting in a decline in the material deposited in the interstices of the fibers [4]. The decline in modulus, strength, and retention of stiffness, which resulted with some of the treatments, could be attributed to the accompanying structural change. As acrylic resins in beater addition might perform differently at different levels of mechanical refinement and wet pressing, a study has been made of refining and wet pressing in relation to beater addition of acrylic resins.

2.2 Experimental

A kraft wood pulp was chosen for this work as it is relatively easy to refine in comparison to rag pulps.

Two acrylic resins were selected for this investigation, E-631 and TR-407 (same as resin HA-16 except for emulsifier). Resin E-631 has an adverse effect on stiffness retention, while TR-407 was found to give the greatest improvement in stiffness retention of any of the acrylic resins investigated in beater addition studies [3]. The use of two greatly different functioning resins would tend to magnify effects and minimize uncertainties due to sample variation.

The pulp was beaten in a PFI laboratory mill at 10 percent consistency, with no clearance between bedplate and roll, for 1, 2.5, 5, 10, or 20 thousand revolutions at 3.4 kilograms force and a relative velocity of roll to bedplate of 6 m/sec. Forty grams of pulp were beaten for each of the variables investigated. Six aliquots were taken from each beater run sufficient to make a 12 x 12 inch handsheet of 70 g/m^2. An aliquot of beater stock was diluted with 600 cm^3 distilled water and agitated 7,500 revolutions in a British disintegrator. If no further treatment was necessary, as in the preparation of waterleaf control handsheets, the mixture was transferred to the deckle box of the handsheet machine and a sheet was made as described below. For acrylic resin treatments, the pH was adjusted to 9 with 1 N NaOH and a retention aid added to the pulp slurry. Two percent, based on latex solids to be deposited on the fibers, was added for latex E-631 and 4 percent for latex TR-407. The retention aid was metered from a 1 percent solution and diluted with 30 cm^3 distilled water. Two thirds of the retention aid was added to the pulp suspension and stirred for 5 minutes in order to exhaust the retention aid from solution prior to latex addition. The pH of the mixture was then decreased to 4.0 with 0.5 N H_2SO_4.

The acrylic emulsion was diluted with approximately 50 cm^3 distilled water and added to the pulp suspension in three equal portions with moderate stirring (rapid stirring removes adsorbed polymer by shearing). Five minutes was allowed between each addition to exhaust the acrylic latex. After all of the latex was added, the remainder of the retention aid was added and the mixture was stirred for an additional 5 minutes.

The mixture was then transferred to the deckle box of the handsheet machine and a sheet was formed. The wire containing the formed sheet was placed on a blotter, covered with a felt, and consolidated by pressing the sheet with a 30 cm long roller weighing 22.5 kg. The sheet was removed from the wire, placed between felts, and passed through the roll press of the handsheet machine at either the minimum or maximum pressure possible. The pressed sheet was dried on a drum drier at 95°C for approximately 4 minutes.

One half of each sheet was flexed 1,000 times over 3.18 mm rollers and constrained by a 700 g free hanging weight on the NBS paper flexer. The other half served as a control. The results are given in Tables 1, 2, 3, and 4.

2.3 Results and Discussion

Wet pressing and mechanical refinement increase the tensile and other physical properties of paper with the exception of Elmendorf tear, cantilever stiffness, air permeability, and thickness. Mechanical refinement results in greater fiber wet flexibility eventuating in greater compaction of fibers before pressing. Therefore, as mechanical refinement is increased, the effect of wet pressing decreases.

The chances for stress concentration increases with density, as when paper is torn, leading to a decrease in tearing strength. Increased compaction of fibers results in a less porous sheet leading to lower air permeability and decreased thickness. The decrease in thickness is also responsible for the decline in bending stiffness, as the stiffness of a material is proportional to the cube of the thickness. It will be shown later, however, that thickness is not the only factor related to the stiffness of paper.

Beater addition of acrylic resins usually increases the porosity of paper. The probable causes for this were discussed in a previous report [2]. The effect of the acrylic resins on the mechanical properties of paper did not appear to be influenced by mechanical treatment. If the stiffness retention of paper retrogressed as a result of treatment with acrylic resin at one set of mechanical treatment conditions, the trend remained unchanged for all the other mechanical treatment conditions. Stiffness retention, as well as the retention of other properties, declined with resin E-631, but improved appreciably with resin TR-407.

The retention of physical properties during flexing increased as the degree of mechanical refinement increased. Wet pressing had a similar effect in that retention of properties with flexing were higher for sheets pressed at the highest pressure.

2.3.1 The Importance of Apparent Density to the Retention of Stiffness with Flexing

Retention of stiffness increases with increasing mechanical refining and wet pressing. Both mechanical processes eventuate higher density paper as the degree of the process increases. A plot of log percent retention of stiffness against density for the four papers investigated indicates a high correlation between the density of the paper and the retention of stiffness with flexing. The coefficient of correlation ranges from .89 for paper treated with E-631 to a high of .99 for the water and retention aid controls (Figure 1).

In the beating of pulp, the following occurs: The outer S_1 layer of the fibers is removed, fibers are cut and split longitudinally, fines are produced, hemicelluloses and other low molecular weight celluloses are rearranged and migrate to the fiber surface or are dissolved, and internal bonds are broken. The fibrils exhibit a significant axial orientation which results in an increase in packing density of the wall [9], and some fibrils are pulled away from the fiber but remain attached (fibrillation) while others break away completely (debris). These morphological changes result in increased wet fiber flexibility and increased fiber strength, stiffness, and modulus upon drying [9]. As the amount of mechanical refinement increases, dislocations and other fiber wall damage occur which reduces both fiber tensile strength and modulus.

Increased wet fiber flexibility results in a more compact fiber network structure or a denser sheet. The fines formed during beating also contribute significantly to sheet density since they produce denser sheets than fibers alone [9]. As a consequence, increased refining results in the production of increasingly more dense sheets with a decreasing amount of free volume, which is the probable cause for increased stiffness retention.

In less dense sheets, the free volume is greater, allowing fibers to move laterally or to twist when strained, permitting the dissipation of stresses in the direction of least resistance. The matrix, located in the interstices of fibers in the sheet and formed from the fines generated during beating, restrains lateral movement and fiber twisting when paper is strained and results in a higher modulus. On flexing, the matrix cracks leaving only the fiber network structure and fiber stiffness contributing to sheet stiffness.

As paper density increases, the matrix contributes less and less to paper stiffness as the decrease in free volume precludes fiber twisting or lateral movement when the paper is strained. If there is little or no degradation of inter-fiber bonding during flexing of dense papers, the free volume should not increase appreciably and the bending stiffness should not decline as extensively as it does in less dense papers.

In summary, the bending stiffness of paper is dependent on (1) fiber stiffness, (2) the matrix formed from the fines, and (3) the fiber network structure. The matrix plays a major role in paper stiffness with less dense papers. Once the matrix is destroyed in flexing, there is a sharp decline in stiffness, and the residual stiffness depends upon the fiber stiffness and fiber network structure. As the fiber network becomes more compact, the free volume of paper declines, and the matrix becomes decreasingly important for paper stiffness. The lower the free volume, the lower the opportunity for fibers to twist and move laterally when paper is strained, resulting in a higher modulus and bending stiffness.

2.3.2 The Relationship Between Paper Modulus and Paper Stiffness

When a piece of material, initially straight, is stressed in bending, the relationships between the applied bending moment and the deformation, on the one hand, and between the deformation and the stress at any point in the material, on the other hand, are given by the ordinary elastic formulae of strength of materials.

$$\frac{M}{I} = \frac{E}{R} = \frac{f}{y}$$

where M = bending moment
I = second moment of area of the section about the neutral plane
E = Young's modulus
R = radius of curvature
f = the tensile or compressive stress in the material at any distance (y) from the neutral plane.

For a rectangular section, as in the case of paper,

$$I = \frac{a\ b^3}{12}$$

where a = width
b = depth of the cross-section (thickness) [13].

In bending, both the stress and the strain vary linearly across the section, increasing from zero at the neutral plane to a maximum at the maximum value of y, providing the material behaves elastically. The stress distribution is represented in Figure 5 below.

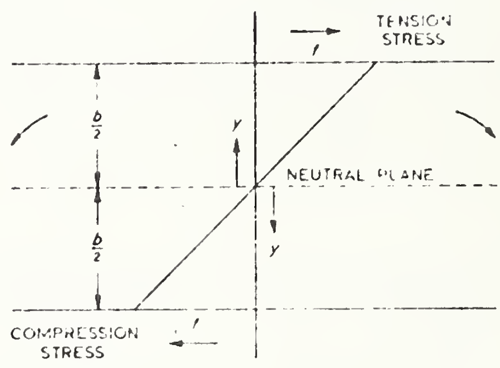

Figure 5. Elastic stress distribution in bending.

Material on the outside of the bend is in tension while that on the inside is in compression [13].

For most materials there is a linear relationship between the modulus and the stiffness of the material, i.e., the stiffness increases with increasing modulus. With paper the reverse is true in that the stiffness decreases with increasing modulus at a constant cellulose content (weight per unit area)(Figure 2). The increase in paper density is achieved by increased beating and wet pressing which results in a decreased thickness if the weight per unit area remains unchanged. As the stiffness of a material is related to the third power of its thickness, it is only logical to attribute the inverse relationship of modulus and stiffness of paper to the decline in thickness.

The relationship between the modulus and the stiffness of flexed paper is the inverse of that for unflexed paper and identical to that of most materials (Figure 3). Since the thickness of flexed and unflexed papers is not significantly different, it becomes apparent that the stiffness of unflexed paper is highly dependent on a structural component which deteriorates during flexing. Conceivably, it is the deterioration of the matrix which has a significant effect on the original stiffness of paper. The effect of the matrix on the stiffness of paper could be viewed as being analogous to the effect of starch on the stiffness of woven or nonwoven fabrics. The matrix in paper and the starch in the woven fabric probably function similarly in increasing the stiffness of the material.

2.4 Achievement of Maximum Density for Currency Paper

The most common methods for increasing the apparent density of paper are (1) mechanical refining (beating), (2) wet pressing, (3) calendering, (4) selecting pulps with low fiber coarseness, and (5) additives such as inorganic fillers.

The morphological changes that occur in fibers during beating were enumerated in section 2.3.1 of this report. Perhaps the most important changes occurring during mechanical refining are the increase in wet fiber flexibility and production of fines. These two factors have a great effect on the final density of paper. Since excessive beating leads to fiber damage, there is a limit to the degree a pulp can be beaten without suffering a decline in strength. Each pulp has a characteristic response to beating which must be determined in advance.

The greatest increase in apparent density through wet pressing is with lightly beaten pulps since these pulps do not compact well without wet pressing. Excessive wet pressing may cause fiber damage and a resulting decline in strength properties. The main advantage in achieving greater density through wet pressing of lightly refined pulp is to obtain high interfiber bonding while still maintaining a lower fiber modulus. In this way, high modulus paper increases its ability to absorb shock and distribute stresses. There is no information available on the effect of wet pressing on subsequent calendering. Some work in this area

is in progress at NBS. The importance of wet pressing in optimizing the apparent density of currency paper is unknown.

Calendering is very effective in increasing the apparent density of paper. However, while calendering makes paper more uniform in thickness, it is at the expense of uniformity in density. Calendering is achieved with a set of horizontal cast iron rolls with chilled hardened surfaces, or a set of rolls having alternate chilled, cast iron, and soft rolls (supercalendering).

Technically, currency paper is supercalendered during printing as it is passed twice between a steel roll consisting of the engraved plate and the flexible impression roll. There is a 20-25 percent reduction in thickness as a consequence of printing.

In retrospect, the dry process for printing currency may have a significant effect on the increased circulation life of currency printed by that method over currency printed by the wet intaglio process [12]. The apparent density of currency (calculated from the weight per unit area and thickness of currency) printed by the wet intaglio method is approximately .791 while currency printed by the dry method is approximately .901. This represents an increase of almost 14 percent in apparent density. The increase should contribute significantly to the increased circulation life of currency printed by the dry intaglio process.

The contribution of density (and, therefore, compressibility) to printability of currency paper has not been established. This needs further study.

Fiber coarseness, the ratio of fiber length to fiber diameter, is an important property of papermaking pulps. It determines the felting characteristics of the fiber. Included in the coarseness factor are fiber thickness, the size of the lumen, and the density of the material making up the fibers. Other factors being equal, the density of the paper is an inverse function of the coarseness of the pulp.

Pulp coarseness is variable in wood pulps but not in rag pulps. Coarseness decreases as fibers are split with beating. However, wood fibers do not easily split apart lengthwise so that their decrease in coarseness with beating is minor and not nearly as marked as with cotton and especially linen fibers. The ability of cotton and linen to decrease in coarseness during beating probably accounts

for the high durability of many rag papers. It is important, however, to beat rag pulps in a manner which will produce maximum longitudinal splitting and a minimum of fiber cutting.

The incorporation of fillers in paper usually results in higher paper densities as the pigments used are much more dense than cellulose. Unfortunately, as the amount of filler increases, the strength decreases because the filler interferes with interfiber bonding. Of the five most common means of increasing paper density (mentioned above), the addition of fillers would appear to have the least utility.

The most effective means of achieving maximum densification of currency paper are mechanical refinement and calendering. Additional information must be obtained on wet pressing before its role in densification can be established.

2.5 Analysis of the Modification of Currency Paper with Acrylic Resins

The main purpose for treating currency paper with acrylic resins is to produce a more crack resistant matrix. This has been discussed in section 2.3.1 of this report.

Two methods are commonly used for modifying paper with latexes: (1) beater addition and (2) saturation. In beater addition, the fibers essentially are encapsulated with resin prior to sheet formation. The second technique involves saturating dry paper with latex, squeezing out the excess, and drying. The saturation technique deposits resin only on the exposed portion of the fibers.

A cursory examination of the two methods favors beater addition over saturation for modifying paper. The intimate mixing of resin with the fines would appear to be an excellent means for improving the crack resistance of the matrix. All that would be necessary is to choose an appropriate resin in sufficient quantity. Unfortunately, treatment of pulps with acrylic resins usually results in a decline of matrix formation [4]. As a consequence, stiffness retention has declined. A combination of treatments (beater addition with an acrylic resin followed by treatment with

a wet strength resin) has overcome the decline of matrix formation and conceivably the double treatment could produce currency paper with a substantial improvement in stiffness retention.

When paper is bent, one side of the paper is in tension, while the other side is in compression (see section 2.3.2 of this report). The higher the tensile and compression moduli, the greater the stiffness of a given paper. The amount of tension and compression also will be dependent on the radius of curvature of the bend. The degree of tension or compression through the sheet is in proportion to the distance from a central neutral plane which is neither in tension or compression. Therefore, the outermost layers of paper have the greatest effect on the stiffness of paper, as these layers are in greatest tension or compression. From this it is apparent that the outermost layers of paper should be modified with resin to achieve maximum stiffness and stiffness retention. When currency paper is modified with a synthetic resin by the saturation technique, most of the resin is taken up by the outer layers. For a given weight gain of acrylic resin, greater stiffness retention should result from saturation than from beater addition by virtue of the resin being located in the areas where it is needed most. In fact, studies have indicated that stiffness retention improves most when paper is treated with acrylic resins by saturation [2].

3. MODIFICATION OF CURRENCY PAPER WITH ACRYLIC RESINS BY THE SATURATION TECHNIQUE

3.1 Background

All previous work on modifying paper with acrylic resins by saturation was done with handsheets. This may not be equivalent to treatment of machine made papers. Consequently, currency paper was saturated with an acrylic resin to determine whether improvements in stiffness retention, similar to those observed with acrylic resin modified handsheets, could be produced.

3.2 Experimental

Some nondistinctive, unsized currency paper was obtained from the manufacturer of U.S. currency paper. The acrylic resin used in this investigation was AC-61, as it produced the best results in saturation of all the acrylic resins evaluated.

One set of 30 x 30 cm sheets of waterleaf (unsized) currency paper was glue-sized by the manufacturer of the paper. As the weight of the sized sheets was approximately 104 g/m^2, it was apparent that the glue content was much greater than normally found in currency paper. Therefore, a second set of 30 x 30 cm sheets was sized at the National Bureau of Standards using a glue-glycerin size mixture employed by the currency paper manufacturer. The sizing was done with the aid of a laboratory size press. The glue-glycerin size mixture was heated and maintained at 63°C. The paper was passed through the sizing solution at a speed sufficient to give a residence time in the sizing mixture of approximately 1.5 seconds. This is the approximate residence time in the sizing mixture at the paper mill. The weight of the NBS sized currency paper was 91 g/m^2 which is considerably closer to the normal weight of currency paper.

Saturation with AC-61 was also done with the aid of the laboratory size press. The emulsion, as received, contained 46.5 percent solids and this was diluted to 20 percent solids with a 3:1 mixture of water and ethanol. Ethanol was used to make the diluted emulsion more hydrophobic. Currency paper has considerable resistance to wetting with water and the treatment with the diluted emulsion was very nonuniform

when ethanol was not used in the dilution. The paper was passed through the size press at about 5 cm/min. and at a pressure of 1.4 kg/cm^2. It was estimated that the residence time of the paper in the saturating medium was about 6 seconds. The saturated sheet was dried on a drum dryer at 95°C for approximately 4 minutes. Each 30 x 30 cm sheet was cut in half. One half was designated for flexing and the remaining half was used for the unflexed control.

Flexing was performed on the NBS paper flexer over 3.18 cm diameter rollers in the cross direction of the paper for 1,000 double flexes. That portion of the specimen passing over both rollers was used for subsequent testing. The air permeability of each specimen was measured in six different locations with a commercial air permeability tester. The sample was then cut into eight specimens as described in NBSIR 74-571 [5].

Cantilever stiffness was measured on the Carson-Worthington stiffness tester [11]. These same specimens were then used for the determination of internal tear according to TAPPI T414 ts-65. A single specimen was used for each determination on an Elmendorf tear tester with a capacity of 200 g. Folding endurance was determined according to TAPPI T511 su-69 using an MIT folding endurance tester.

Load elongation was performed on a constant rate of elongation apparatus according to TAPPI T404 ts-66, using a specimen 1.5 cm wide and a span length of 10 cm.

The results are given in Tables 5 and 6.

3.3 Results and Discussion

The data indicate that currency paper treated with AC-61 has far better stiffness retention after flexing than when sized with a glue-glycerin mixture. Furthermore, the acrylic resin treated currency paper has a higher strength and energy to break than the glue-sized paper. Retention of stiffness after 1,000 flexes is only 61 percent for glue-sized paper as compared to 86 percent for the resin-treated paper (Figure 4).

Increasing the glue-glycerin content from approximately 6 to 18 percent results in a softer paper. The stiffness of the glue-sized papers after flexing are not significantly different but, as the stiffness of the unflexed paper containing the greater amount of glue-glycerin is much lower, the retention naturally is much higher (Figure 4). Ideally, however, currency should have a high stiffness initially and it should maintain that stiffness to a high degree when flexed.

Perhaps the greatest advantage in glue sizing is the improvement in folding endurance. However, even though the higher glue-glycerin content currency paper has a significantly higher folding endurance, it does not appear to be more durable. This is an important point to consider in evaluating potential currency papers. Great emphasis may be placed on high folding endurance on the assumption that it is synonymous with durability. Unfortunately, a relatively poor paper might appear to be high quality if treated with a sufficient amount of glue-glycerin to impart high folding endurance.

This investigation suggests that a mill trial should be conducted by modifying currency paper with AC-61 acrylic resin by saturation. This would enable a full scale evaluation of the paper. Along with the acrylic treated paper, the evaluation should include some unsized and some glue-sized paper from the same lot. A minimum of 10 percent AC-61 resin should be applied to the paper in a uniform manner. All three papers should be printed.

In addition to evaluating the printability of the paper and its subsequent durability, there should be an investigation on the repulpability of the resin treated paper. It is essential that all the currency paper wastes, along with trimmings from printed currency, be repulpable for reasons of economy.

If the AC-61 treated currency paper maintains its superior stiffness retention after printing, a substantial increase in circulation life of currency might result, providing all other factors remain unchanged. New factors influencing circulation life may arise as a consequence of the treatment or because of the extended circulation life. Therefore, the new currency would have to be placed in circulation and monitored before a final assessment of the paper could be made.

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Table 1. The Effect of Beating, Wet Pressing, and Acrylic Resins on the Tensile Properties of Wood Pulp Handsheets

PFI Revolutions 1,000	Wet[1] Pressing Pressure	No. of Specimens		Modulus kg/cm^{2}x10^{-3}				Breaking Strength kg				Elongation to Break %				Energy to Break kg-cm			
		W[2]	L[2]	W	s[3]	L	s	W	s	L	s	W	s	L	s	W	s	L	s
Water Control																			
1	L	6	6	16.6	1.2	15.1	1.3	3.6	0.2	3.5	0.3	2.6	0.2	2.3	0.3	0.7	0.06	0.5	0.10
1	H	6	6	19.3	1.2	20.3	2.0	4.1	0.2	4.4	0.2	2.8	0.2	2.6	0.2	0.8	0.09	0.8	0.07
2.5	L	6	6	24.4	1.4	22.5	1.8	5.6	0.2	5.3	0.4	3.6	0.1	2.9	0.3	1.4	0.09	1.1	0.1
2.5	H	6	6	26.3	1.4	27.6	2.3	5.7	0.6	6.2	0.4	3.5	0.5	3.0	0.1	1.4	0.3	1.2	0.09
5	L	6	6	32.8	3.3	29.3	3.2	7.3	0.4	7.0	0.3	3.8	0.2	3.4	0.2	1.8	0.2	1.5	0.07
5	H	6	6	31.9	2.1	34.4	2.7	7.0	0.5	7.8	0.4	4.1	0.4	3.5	0.2	1.9	0.3	1.8	0.1
10	L	6	6	37.1	3.0	37.3	1.6	8.0	0.7	8.4	0.4	4.2	0.4	3.9	0.2	2.2	0.4	2.1	0.2
10	H	6	6	39.7	1.3	41.2	4.5	8.5	0.5	8.8	0.6	4.4	0.3	3.7	0.4	2.4	0.3	2.1	0.3
20	L	6	6	39.6	2.8	39.4	3.0	8.7	0.5	8.7	0.5	4.4	0.5	4.1	0.3	2.5	0.4	2.3	0.2
20	H	6	5	40.7	2.3	41.4	2.8	9.1	0.3	9.7	0.6	4.9	0.2	4.3	0.1	2.9	0.1	2.7	0.2
Retention Aid Control																			
5	L	6	6	28.2	1.5	24.6	1.5	6.9	0.5	6.4	0.9	3.9	0.3	3.5	0.5	1.8	0.2	1.5	0.4
5	H	6	6	31.5	1.2	31.8	2.8	7.8	0.2	8.4	0.7	4.5	0.1	4.1	0.2	2.3	0.07	2.2	0.2
10	L	6	6	35.0	2.1	29.6	1.2	8.1	0.2	7.9	0.4	4.1	0.2	4.2	0.2	2.2	0.1	2.2	0.2
10	H	5	6	34.1	1.6	34.3	3.7	8.6	0.5	8.6	0.4	4.8	0.3	3.9	0.2	2.7	0.3	2.2	0.1
20	L	5	5	42.5	3.2	37.7	1.7	9.2	0.8	9.1	0.3	4.4	0.3	4.3	0.2	2.6	0.3	2.6	0.2
20	H	6	6	40.4	1.5	39.4	2.4	9.3	0.4	9.7	1.0	5.0	0.3	4.5	0.2	3.0	0.3	2.7	0.3
Treated with 10% E-631 Acrylic Resin by Beater Addition																			
5	L	6	6	25.8	2.3	27.4	2.6	6.0	0.4	6.4	0.5	4.1	0.3	3.6	0.2	1.7	0.1	1.6	0.2
5	H	6	6	29.1	2.2	29.8	3.3	6.1	0.6	6.5	0.7	4.0	0.3	3.6	0.2	1.7	0.3	1.6	0.2
10	L	6	6	29.9	2.0	29.1	1.9	7.0	0.4	7.4	0.3	4.5	0.3	4.2	0.4	2.1	0.2	2.0	0.3
10	H	6	6	30.0	3.8	32.9	2.3	7.6	0.6	7.9	0.4	4.8	0.6	4.0	0.4	2.4	0.3	2.1	0.2
20	L	6	6	26.6	3.0	30.3	3.2	7.2	0.8	7.6	0.7	4.9	0.5	4.2	0.4	2.3	0.4	2.1	0.3
20	H	6	5	30.6	2.8	35.9	3.2	8.3	0.3	8.5	0.3	5.4	0.5	4.7	0.3	2.9	0.3	2.6	0.1
Treated with 10% TR-407 Acrylic Resin by Beater Addition																			
5	L	5	5	28.0	1.7	28.2	2.2	8.5	0.3	9.1	0.4	4.6	0.3	4.3	0.1	2.5	0.2	2.5	0.8
5	H	5	6	32.3	1.7	32.4	0.8	8.8	0.5	9.7	0.5	4.8	0.3	4.3	0.3	2.7	0.3	2.6	0.3
10	L	4	4	33.1	2.6	33.5	2.4	10.2	0.5	10.1	0.3	5.0	0.6	4.6	0.1	3.2	0.4	3.0	0.1
10	H	4	4	33.1	1.0	36.8	2.5	9.8	0.8	10.6	0.3	5.1	0.6	4.4	0.2	3.2	0.6	3.0	0.2
20	L	5	6	37.7	1.4	39.3	2.0	10.1	0.4	10.1	1.0	5.1	0.3	4.4	0.4	3.3	0.2	2.9	0.5
20	H	5	5	37.0	1.7	38.5	3.1	10.4	0.4	10.1	1.2	5.5	0.1	4.4	0.4	3.6	0.2	2.8	0.5

PFI Revolutions 1,000	Wet[1] Pressing Pressure	Load at Yield kg				Elongation at Yield %				Plastic Modulus kg/cm^{2}x10^{-3}				Thickness µm			
		W	s	L	s	W	s	L	s	W	s	L	s	W	s	L	s
Water Control																	
1	L	2.6	0.2	2.6	0.03	0.7	0.04	0.7	0.09	2.3	0.1	2.6	0.2	155	3	166	3
1	H	2.9	0.1	2.9	0.25	0.7	0.04	0.7	0.08	2.6	0.2	3.5	0.4	143	4	148	3
2.5	L	3.6	0.3	3.4	0.3	0.7	0.04	0.7	0.06	3.4	0.3	3.9	0.3	140	2	150	4
2.5	H	3.4	0.3	3.7	0.2	0.7	0.03	0.7	0.08	4.2	0.5	5.3	0.7	134	4	135	3
5	L	4.0	0.3	4.2	0.4	0.7	0.08	0.7	0.04	5.5	0.4	5.1	0.4	127	5	138	5
5	H	3.9	0.3	4.1	0.2	0.7	0.06	0.7	0.07	5.2	0.5	6.7	0.7	122	3	126	4
10	L	4.0	0.3	4.2	0.3	0.7	0.1	0.6	0.07	6.3	0.5	6.6	0.3	115	4	125	3
10	H	4.0	0.2	4.4	0.2	0.6	0.02	0.6	0.05	6.8	0.7	8.0	1.1	113	5	119	5
20	L	4.4	0.3	4.5	0.2	0.8	0.09	0.7	0.05	6.9	0.3	6.8	0.4	110	4	117	3
20	H	4.2	0.2	4.5	0.2	0.6	0.06	0.7	0.06	6.4	0.4	7.7	0.3	112	2	114	3
Retention Aid Control																	
5	L	3.7	0.08	3.6	0.2	0.6	0.02	0.7	0.03	4.9	0.4	4.4	0.4	138	6	150	3
5	H	3.7	0.3	3.9	0.3	0.6	0.03	0.6	0.01	5.4	0.2	6.5	0.9	127	2	133	2
10	L	4.1	0.1	4.0	0.2	0.7	0.05	0.7	0.05	6.1	0.3	5.3	0.3	126	5	138	6
10	H	4.1	0.1	4.3	0.2	0.7	0.04	0.7	0.1	5.8	0.3	6.9	0.4	122	3	125	2
20	L	4.6	0.2	4.5	0.1	0.7	0.02	0.7	0.04	7.2	0.8	6.7	0.5	115	5	121	3
20	H	4.4	0.05	4.6	0.3	0.7	0.03	0.7	0.05	6.2	0.4	7.2	0.9	113	3	118	4
Treated with 10% E-631 Acrylic Resin by Beater Addition																	
5	L	3.8	0.1	4.1	0.2	0.7	0.04	0.7	0.06	3.1	0.8	3.8	0.5	140	2	143	3
5	H	3.9	0.5	4.0	0.5	0.7	0.05	0.7	0.05	3.8	0.8	4.6	0.8	127	5	131	4
10	L	3.8	0.4	4.0	0.5	0.7	0.09	0.7	0.1	4.4	0.5	5.1	0.6	129	4	134	5
10	H	3.7	0.5	4.1	0.4	0.6	0.06	0.7	0.07	5.1	0.8	6.1	0.8	127	5	126	4
20	L	3.5	0.4	3.7	0.3	0.7	0.1	0.7	0.05	4.6	0.8	5.6	0.6	128	3	127	8
20	H	3.7	0.2	3.9	0.3	0.7	0.03	0.6	0.05	5.0	0.7	6.2	0.6	123	2	115	2
Treated with 10% TR-407 Acrylic Resin by Beater Addition																	
5	L	3.6	0.1	4.3	0.2	0.6	0.04	0.7	0.04	5.4	0.2	6.0	0.5	144	2	149	3
5	H	3.7	0.1	4.3	0.2	0.6	0.04	0.7	0.04	5.9	0.3	7.3	0.5	131	2	135	1
10	L	4.1	0.2	4.3	0.1	0.6	0.04	0.6	0.05	6.5	0.3	6.6	0.2	132	4	140	4
10	H	4.2	0.1	4.7	0.2	0.7	0.02	0.7	0.06	6.2	0.4	7.6	0.3	127	3	131	3
20	L	4.4	0.2	4.6	0.2	0.6	0.02	0.6	0.03	6.3	0.3	7.1	0.4	124	4	129	3
20	H	4.4	0.2	4.6	0.3	0.7	0.03	0.7	0.04	6.3	0.2	7.3	0.5	121	2	126	3

[1]Wet sheets were pressed at either minimum (L) or maximum (H) pressure possible.
[2]W = width and L = length of 15 x 30 cm flex samples.

$$^{3}s = \sqrt{\frac{n\Sigma x^2 - (\Sigma x)^2}{n(n-1)}}$$

Table 2. The Effect of Beating, Wet Pressing, and Acrylic Resins on the Tensile Properties of Wood Pulp Handsheets After Flexing[1]

PFI Revolutions 1,000	Wet[2] Pressing Pressure	No. of Specimens		Modulus kg/cm^{2}x10^{-3}				Breaking Strength kg				Elongation to Break %				Energy to Break kg/cm				Load at Yield kg				Elongation at Yield %				Plastic Modulus kg/cm^{2}x10^{-3}				Thickness µm			
		W[3]	L[3]	W	s[4]	L	s	W	s	L	s	W	s	L	s	W	s	L	s	W	s	L	s	W	s	L	s	W	s	L	s	W	s	L	s
Water Control																																			
1	L	5	6	10.0	1.0	5.5	0.6	2.8	0.1	3.1	0.2	2.9	0.5	3.0	0.2	0.3	0.06	0.5	0.07	2.0	0.1	2.5	0.3	0.9	0.07	2.0	0.3	1.7	0.3	2.9	0.4	161	4	162	3
1	H	6	6	11.5	1.3	7.3	0.7	3.1	1.8	3.8	0.3	3.1	0.3	3.0	0.3	0.3	0.04	0.6	0.08	2.3	0.2	3.1	0.7	1.0	0.1	2.0	0.5	1.9	0.5	3.9	0.8	146	4	145	1
2.5	L	5	6	16.9	4.7	9.4	0.9	4.5	0.5	4.9	0.5	3.6	0.6	3.3	0.2	0.5	0.07	0.9	0.2	3.1	0.5	3.5	0.3	0.9	0.1	1.7	0.2	2.4	0.5	4.4	0.4	144	3	144	2
2.5	H	6	6	19.0	1.2	14.0	1.6	4.8	0.3	5.7	0.3	3.3	0.2	3.4	0.3	1.0	0.1	1.1	0.1	3.0	0.2	3.7	0.6	0.8	0.1	1.4	0.2	3.7	0.4	5.5	1.6	134	3	130	4
5	L	5	6	23.8	2.4	15.3	2.3	6.5	0.4	6.4	0.5	3.8	0.4	3.7	0.1	1.6	0.2	1.4	0.1	3.4	0.3	4.0	0.3	0.8	0.1	1.4	0.2	5.1	0.4	5.3	0.9	131	5	131	5
5	H	6	6	26.2	1.4	20.0	2.3	6.5	0.3	7.4	0.5	4.0	0.2	3.6	0.3	1.7	0.1	1.6	0.2	3.1	0.1	4.0	0.5	0.6	0.02	1.1	0.3	5.5	0.2	7.8	0.6	122	3	120	4
10	L	6	6	31.4	1.2	22.3	1.5	7.9	0.6	8.1	0.9	4.5	0.4	4.0	0.4	2.3	0.3	1.9	0.4	3.6	0.3	4.4	0.7	0.6	0.04	1.1	0.2	5.9	0.2	7.2	0.3	120	2	118	3
10	H	6	5	30.5	0.9	28.9	4.4	7.9	0.4	8.4	0.4	4.6	0.5	3.7	0.3	2.3	0.3	1.9	0.2	3.6	0.2	4.2	0.2	0.7	0.03	0.9	0.2	6.2	0.5	9.2	0.3	115	3	110	2
20	L	6	6	34.8	4.0	29.0	1.7	8.6	0.4	8.8	0.4	4.8	0.5	4.4	0.06	2.7	0.3	2.4	0.1	3.9	0.3	4.4	0.3	0.7	1.0	0.9	0.1	6.4	0.5	7.9	0.3	111	4	107	3
20	H	5	5	33.0	4.0	32.9	2.3	8.4	0.3	9.2	0.4	4.9	0.4	4.2	0.2	2.6	0.2	2.4	0.2	3.8	0.04	4.4	0.07	0.7	0.2	0.9	0.07	6.4	0.4	9.2	0.4	110	2	103	1
Retention Aid Control																																			
5	L	6	6	21.8	1.2	11.6	1.6	6.2	0.3	6.0	0.4	4.1	0.3	4.0	0.2	1.7	0.1	1.4	0.2	3.5	0.3	3.7	0.5	0.8	0.07	1.5	0.3	3.9	0.7	4.5	0.5	141	2	141	5
5	H	6	6	25.2	1.3	17.6	1.3	6.8	0.3	7.5	0.3	4.5	0.2	4.1	0.2	2.0	0.2	1.8	0.08	3.4	0.3	4.1	0.5	0.7	0.06	1.3	0.1	4.7	0.4	6.5	0.8	130	2	125	2
10	L	6	6	28.3	0.7	17.4	1.9	7.8	0.1	7.4	0.4	4.4	0.2	4.1	0.2	2.2	0.1	1.8	0.2	3.6	0.3	4.0	0.4	0.7	0.1	1.3	0.2	5.9	0.4	6.6	0.4	125	3	125	3
10	H	6	6	29.4	1.4	25.2	2.0	7.6	0.8	8.3	0.3	4.5	0.3	4.0	0.2	2.2	0.4	2.0	0.2	3.4	0.2	4.2	0.4	0.7	0.04	1.0	0.2	5.7	0.4	7.8	0.6	122	1	117	1
20	L	6	5	33.4	2.9	26.6	3.8	8.0	0.5	8.7	0.6	4.4	0.4	4.4	0.2	2.3	0.3	2.3	0.2	3.8	0.2	4.4	0.3	0.7	0.1	1.0	0.2	6.6	0.5	7.7	0.5	134	4	112	3
20	H	6	5	33.6	2.7	32.5	1.4	8.3	0.6	8.7	0.2	5.1	0.2	4.4	0.06	2.7	0.2	2.4	0.06	3.7	0.2	4.2	0.2	0.7	0.06	0.8	0.05	5.7	0.6	7.8	0.4	114	2	106	1
Treated with 10% E-631 Acrylic Resin by Beater Addition																																			
5	L	6	6	17.5	3.0	11.4	1.1	5.1	0.5	5.6	0.5	4.1	0.3	3.9	0.5	1.4	0.1	1.3	0.2	3.3	0.6	4.0	0.6	0.9	0.09	1.7	0.3	2.9	0.7	3.7	0.8	138	4	139	2
5	H	6	5	19.7	2.4	17.0	1.2	5.7	0.5	6.6	0.6	4.1	0.3	3.8	0.2	1.5	0.2	1.5	0.1	3.6	0.5	4.3	0.7	1.0	0.09	1.3	0.2	3.6	0.7	5.2	1.0	127	5	125	4
10	L	6	6	20.9	2.8	15.1	1.4	6.3	0.5	6.8	0.2	4.9	0.4	4.2	0.2	2.0	0.2	1.7	0.09	3.6	0.5	4.5	0.6	0.9	0.1	1.6	0.4	3.5	0.3	4.7	0.7	129	2	127	4
10	H	5	5	23.6	3.7	20.9	1.9	6.7	0.5	7.5	0.6	5.0	0.7	4.4	0.6	2.1	0.4	2.0	0.4	3.5	0.4	4.0	0.6	0.9	0.1	1.1	0.2	4.3	0.4	5.8	0.6	121	2	120	2
20	L	6	6	25.4	2.2	18.0	1.6	7.2	0.2	7.4	0.5	4.7	0.4	4.1	0.2	2.2	0.2	1.8	0.2	3.9	0.5	4.5	0.5	0.9	0.2	1.3	0.2	4.5	0.8	5.6	0.5	126	1	125	3
20	H	6	6	27.2	1.8	25.1	2.3	7.7	0.5	8.1	0.2	5.2	0.5	4.6	0.3	2.5	0.2	2.3	0.2	3.4	0.5	4.4	0.7	0.7	0.09	1.1	0.2	5.2	0.6	6.2	0.9	119	4	116	2
Treated with 10% TR-407 Acrylic Resin by Beater Addition																																			
5	L	6	6	25.1	1.4	16.2	3.1	8.1	0.3	7.8	0.6	4.6	0.2	4.1	0.3	2.4	0.2	1.9	0.3	3.5	0.5	4.0	0.7	0.6	0.11	1.2	0.41	5.2	0.6	6.0	0.7	105	4	145	4
5	H	4	6	28.3	0.7	25.6	1.5	8.7	0.5	8.7	0.3	4.9	0.3	3.9	0.2	2.6	0.3	2.1	0.2	3.6	0.6	4.2	0.5	0.6	0.12	0.8	0.09	6.0	0.4	7.4	0.8	133	3	130	2
10	L	4	3	30.0	1.0	25.0	2.4	9.4	0.7	9.1	0.8	4.9	0.3	4.3	0.2	2.9	0.4	2.4	0.3	3.7	0.1	4.5	0.02	0.6	0.10	0.9	0.07	6.2	0.3	6.8	0.7	134	3	133	4
10	H	3	4	33.5	1.2	31.7	0.8	9.8	0.3	9.8	0.2	5.1	0.3	4.2	0.1	3.1	0.2	2.5	0.1	4.0	0.1	4.8	0.4	0.6	0.03	0.8	0.07	6.3	0.2	8.0	0.5	129	2	125	3
20	L	5	5	36.7	2.0	31.8	2.3	10.0	0.4	9.9	0.6	5.0	0.2	4.4	0.3	3.2	0.2	2.7	0.3	4.1	0.1	4.7	0.4	0.6	0.02	0.8	0.08	6.7	0.2	7.8	0.4	125	3	122	3
20	H	6	6	35.4	1.3	34.5	0.6	[illegible]	0.6	10.0	0.4	5.3	0.3	4.4	0.3	3.3	0.4	2.9	0.3	4.1	0.2	4.6	0.3	0.6	0.02	0.7	0.04	6.3	0.3	8.1	0.2	122	2	120	3

[1]Handsheets were flexed 1,000 times over 3.18 mm rollers and constrained by a 700 g free hanging weight.
[2]Wet sheets pressed at either minimum (L) or maximum (H) pressure possible.
[3]W = width and L = length of 15 x 30 cm flex samples.

[4]$s = \sqrt{\frac{n\Sigma x^2 - (\Sigma x)^2}{n(n-1)}}$

Table 3. The Effect of Beating, Wet Pressing, and Acrylic Resins on the Physical Properties of Wood Pulp Handsheets.

PFI Revolutions 1,000	Wet[1] Pressing Pressure	No. of Specimens W^2	L^2	Elmendorf Tear g W	s^3	L	s	MIT Fold Endurance 1000 g, double folds W	s	L	s	Cantilever Stiffness g-cm W	s	L	s	Sonic Modulus[4] kg/cm^{2}x10^{-4} W	s	L	s	Air Permeability ml/min (10cm)	s	Weight per Unit Area g/m^2	Apparent Density g/cm^3 W	s	L	s
Water Control																										
1	L	6	6	91	9	85	8	41	9	44	17	2.6	0.1	2.6	0.1	9.5	0.4	9.8	0.5	2669	88	68	.442	.008	.410	.008
1	H	6	6	91	5	87	5	75	31	104	26	2.1	0.2	2.1	0.2	10.0	0.4	10.8	0.4	1782	53	68	.474	.013	.458	.008
2.5	L	6	6	99	8	100	11	498	160	350	105	2.4	0.1	2.4	0.07	11.6	0.2	12.0	0.5	1628	171	69	.489	.007	.458	.013
2.5	H	6	6	90	11	96	5	600	159	604	159	1.9	0.1	1.8	0.2	12.0	0.3	12.8	0.9	896	72	68	.511	.016	.505	.012
5	L	6	6	89	12	94	11	1235	162	1283	341	2.3	0.1	2.1	0.2	13.5	0.3	13.2	0.9	834	175	68	.537	.020	.493	.019
5	H	6	6	78	13	87	13	1373	181	1466	175	1.9	0.1	1.8	0.2	12.9	0.4	14.0	0.6	360	39	68	.558	.015	.541	.017
10	L	6	6	77	11	80	16	1778	463	1675	347	2.0	0.2	2.0	0.2	13.9	0.7	13.7	0.6	233	29	68	.594	.020	.544	.014
10	H	6	6	67	7	68	10	2178	225	2316	478	1.7	0.1	1.6	0.05	14.3	0.3	15.4	1.2	133	11	68	.604	.024	.572	.023
20	L	6	6	64	10	65	12	2543	687	2373	348	1.6	0.3	1.6	0.1	14.7	0.6	15.0	0.6	55	6	67	.614	.022	.576	.013
20	H	6	6	61	4	61	7	2723	585	2980	650	1.5	0.1	1.4	0.1	13.7	0.6	14.8	0.5	49	4	67	.599	.009	.588	.015
Retention Aid Control																										
5	L	6	6	105	9	93	9	1072	194	1164	295	2.5	0.3	2.4	0.2	12.4	0.4	11.9	0.6	1362	145	69	.501	.021	.461	.011
5	H	6	6	80	14	69	3	1464	206	1680	238	1.9	0.2	1.9	0.1	12.9	0.8	13.1	0.7	371	34	69	.542	.009	.516	.009
10	L	6	6	82	14	80	11	1647	209	1535	271	2.2	0.1	2.2	0.2	13.9	0.5	13.0	0.6	402	81	69	.552	.020	.504	.021
10	H	6	6	70	13	70	9	2410	346	2031	609	1.7	0.2	1.6	0.2	13.3	0.5	13.7	0.5	147	16	69	.566	.012	.551	.010
20	L	6	6	79	9	78	4	1872	546	1935	309	2.0	0.1	1.7	0.1	14.7	0.7	14.7	0.7	95	11	69	.603	.025	.571	.016
20	H	6	6	65	11	66	8	2451	251	2890	560	1.6	0.1	1.4	0.1	14.3	0.5	14.8	0.7	49	3	68	.607	.016	.580	.019
Treated with E-631 Acrylic Resin by Beater Addition																										
5	L	6	6	93	4	92	9	1152	423	1435	336	2.4	0.2	2.5	0.1	11.3	0.5	12.0	0.4	1407	173	76	.548	.016	.533	.012
5	H	6	6	77	5	85	9	1377	509	1313	380	1.9	0.1	2.0	0.2	11.6	0.8	12.0	0.6	674	132	76	.604	.024	.585	.019
10	L	6	6	74	7	85	17	2055	323	1790	506	2.1	0.1	2.0	0.2	12.0	0.6	12.4	0.6	572	86	77	.597	.020	.575	.019
10	H	6	6	80	16	74	10	1995	448	2013	549	1.7	0.1	1.9	0.2	11.5	1.4	12.7	0.9	244	45	77	.611	.026	.615	.019
20	L	6	6	79	11	76	7	2092	269	2194	181	1.9	0.2	2.0	0.1	11.1	1.1	12.6	0.6	218	40	77	.598	.015	.603	.039
20	H	6	6	71	12	69	12	2801	187	2828	589	1.3	0.1	1.8	0.2	11.5	0.5	13.1	0.8	88	10	76	.621	.012	.665	.012
Treated with TR-407 Acrylic Resin by Beater Addition																										
5	L	6	6	83	4	82	11	1775	377	1780	224	2.7	0.2	2.6	0.2	12.9	0.5	12.2	0.4	1044	93	74	.514	.013	.496	.010
5	H	6	6	74	4	73	11	2344	405	2269	361	2.0	0.05	2.1	0.1	12.9	0.6	12.5	0.5	453	38	74	.564	.092	.546	.005
10	L	6	6	95	25	77	5	2556	687	2445	563	2.5	0.2	2.5	0.3	13.7	0.3	13.2	0.4	284	29	76	.579	.016	.545	.014
10	H	5	5	69	8	67	5	3600	776	3779	702	2.1	0.1	2.1	0.2	13.6	0.7	13.9	0.7	113	10	77	.607	.014	.590	.015
20	L	6	6	65	5	70	7	3176	599	3368	614	2.1	0.2	2.1	0.2	14.6	0.7	14.1	0.7	86	14	75	.610	.018	.589	.015
20	H	6	6	61	7	65	8	5070	1600	4296	630	1.8	0.2	2.0	0.2	14.6	0.9	12.8	0.4	57	9	75	.622	.011	.597	.014

[1] Handsheets were consolidated by using either minimum (L) or maximum (H) pressure possible.

[2] W = width and L = length of 15 x 30 cm flex specimens.

[3] $s = \sqrt{\frac{n\Sigma x^2 - (\Sigma x)^2}{n(n-1)}}$

[4] Sonic modulus based on cellulose density of 1.54 g/cm^3.

Table 4. The Effect of Beating, Wet Pressing, and Acrylic Resins on the Physical Properties of Wood Pulp Handsheets After Flexing.

PFI Revolutions 1,000	Wet[2] Pressing Pressure	No. of Specimens		Elmendorf Tear g				MIT Fold Endurance 1000 g, double folds				Cantilever Stiffness g-cm				Sonic Modulus[5] kg/cm^2x10^{-4}				Air Permeability ml/min (10cm)		Apparent Density g/cm^3			
		W[3]	L[3]	W	s[4]	L	s	W	s	L	s	W	s	L	s	W	s	L	s		s	W	s	L	s
Water Control																									
1	L	6	6	78	3	73	6	23	5	23	5	0.7	0.07	0.4	0.03	--		--		2865	89	.425	.011	.421	.009
1	H	6	6	87	9	76	7	48	10	67	31	0.7	0.1	0.4	0.04	--		--		2145	96	.465	.012	.468	.013
2.5	L	6	6	93	6	88	3	315	108	248	132	1.3	0.2	0.6	0.1	--		4.78	0.3	1878	157	.478	.009	.477	.003
2.5	H	6	6	85	4	86	9	476	89	416	233	1.1	0.06	0.6	0.1	--		--		1142	49	.511	.012	.527	.014
5	L	6	6	75	4	86	8	1265	325	730	268	1.4	0.2	0.7	0.05	--		7.1	0.9	976	197	.519	.018	.520	.020
5	H	6	6	81	11	79	9	1328	202	1094	308	1.4	0.09	0.8	0.1	10.1	0.2	9.0	0.6	529	26	.559	.013	.567	.016
10	L	6	6	70	9	79	7	1769	335	1738	341	1.5	0.3	0.9	0.1	11.4	0.3	9.6	0.3	280	31	.568	.012	.557	.012
10	H	6	6	66	9	78	6	2234	380	2121	404	1.3	0.2	0.9	0.05	11.5	0.5	11.7	0.6	159	12	.594	.017	.619	.012
20	L	6	6	66	10	75	15	2231	394	1900	465	1.4	0.1	1.1	0.2	12.0	0.6	11.6	0.5	65	8	.608	.019	.628	.017
20	H	6	6	68	10	63	9	2372	293	2252	687	1.2	0.1	1.1	0.1	11.7	0.4	12.4	0.4	53	3	.610	.011	.648	.003
Retention Aid Control																									
5	L	6	6	92	7	95	12	1275	266	817	188	1.6	0.2	0.7	0.1	8.7	1.4	6.0	0.7	1486	174	.494	.020	.491	.016
5	H	6	6	78	11	83	6	1335	307	1143	223	1.3	0.1	0.8	0.03	9.9	0.3	8.3	0.5	579	60	.530	.010	.551	.011
10	L	6	6	76	9	76	10	1480	462	1499	328	1.6	0.1	0.9	0.05	11.4	0.3	8.6	0.7	502	76	.556	.014	.557	.015
10	H	6	6	73	12	76	12	1773	380	1716	568	1.3	0.1	0.9	0.1	10.9	0.8	10.7	0.3	203	20	.567	.005	.592	.007
20	L	6	6	74	9	82	17	2052	432	2119	404	1.4	0.2	1.0	0.03	11.2	1.9	10.8	0.6	110	9	.608	.019	.619	.019
20	H	6	6	60	5	69	7	2376	616	2056	290	1.3	0.1	1.0	0.1	11.7	0.8	11.8	0.5	58	4	.599	.012	.642	.007
Treated with E-631 Acrylic Resin by Beater Addition																									
5	L	6	6	85	8	84	8	971	191	1092	376	1.3	0.2	0.7	0.05	8.4	0.5	6.3	0.6	1478	192	.554	.015	.550	.017
5	H	6	6	78	9	81	12	1504	400	1338	261	1.1	0.2	0.7	0.07	9.4	0.6	8.8	0.5	699	149	.601	.021	.613	.018
10	L	6	6	72	4	89	14	1830	390	1528	352	1.3	0.2	0.8	0.02	9.2	0.5	8.4	0.5	617	96	.595	.009	.608	.021
10	H	5	5	68	4	67	10	1959	206	2124	423	1.0	0.07	0.8	0.03	10.0	0.7	9.5	0.2	247	61	.639	.013	.645	.011
20	L	6	6	79	11	76	12	2024	125	1675	201	1.4	0.2	0.9	0.05	10.1	0.3	9.2	0.4	240	47	.608	.007	.610	.013
20	H	6	6	69	14	62	4	2513	300	2670	475	1.2	0.2	0.8	0.07	10.6	0.4	10.5	0.4	100	12	.618	.018	.633	.014
Treated with TR-407 Acrylic Resin by Beater Addition																									
5	L	6	6	83	7	87	13	1796	349	1541	321	1.7	0.2	1.2	0.04	10.7	0.4	7.9	0.4	1084	98	.511	.015	.514	.013
5	H	6	5	68	5	78	5	1811	396	1537	434	1.7	0.2	1.3	0.04	11.1	0.5	[illegible]	0.4	460	40	.555	.014	.567	.009
10	L	5	5	72	9	70	4	2527	165	2555	518	2.0	0.2	1.6	0.1	11.8	0.6	9.6	0.7	296	31	.568	.013	.575	.016
10	H	4	4	64	2	68	5	3928	636	3554	445	1.8	0.2	1.4	0.1	11.8	0.4	11.6	0.7	116	12	.599	.007	.620	.013
20	L	6	5	73	7	62	4	2972	554	2858	644	1.7	0.1	1.6	0.1	12.1	0.6	11.2	0.6	92	15	.606	.016	.617	.016
20	H	6	6	60	2	59	7	4162	134	3410	729	1.5	0.2	1.5	0.2	12.3	0.8	11.8	0.4	59	12	.615	.009	.629	.015

[1]Handsheets were flexed 1,000 times over 3.18 mm rollers and constrained by a 700 g free hanging load.

[2]Handsheets were consolidated by using the minimum (L) or maximum (H) pressure possible on handsheet machine.

[3]W = width and L = length of 15 x 30 cm flex specimens.

[4] $s = \sqrt{\frac{n\Sigma x^2 - (\Sigma x)^2}{n(n-1)}}$

[5]Sonic modulus based on cellulose density of 1.54 g/cm^3.

Table 5. The Effect of Glue-Glycerin Sizing and Saturation with Acrylic Resin AC-61 on the Retention of Tensile Properties of Currency Paper After Flexing.

Treatment	No. of Flexes	No. of Specimens		Modulus kg/cm^{2}x10^{-3}				Breaking Strength kg				Elongation to Break %				Energy to Break kg-cm				Load at Yield kg				Elongation at Yield %				Plastic Modulus kg/cm^{2}x10^{-3}			
		M	C	M	s[1]	C	s	M	s	C	s	M	s	C	s	M	s	M	s	M	s	C	s	M	s	C	s	M	s	C	s
none	0	9	10	52.3	3.1	27.3	1.9	10.3	0.6	6.3	0.2	2.9	0.2	5.6	0.7	2.1	0.2	2.7	0.4	7.6	0.4	4.6	0.1	0.8	0.04	0.9	0.07	7.2	0.7	2.0	0.3
glue-glycerin-regular	0	7	7	43.9	1.8	24.4	1.2	10.7	0.6	6.8	0.3	3.8	0.2	7.1	0.9	2.8	0.3	3.5	0.5	6.3	0.5	4.3	0.3	0.7	0.04	0.9	0.04	6.8	0.5	2.0	0.1
glue-glycerin-high	0	8	10	36.8	0.8	18.4	1.4	9.6	0.4	6.4	0.3	4.6	0.3	8.9	0.5	2.9	0.2	3.9	0.4	5.2	0.3	3.2	0.3	0.7	0.06	0.9	0.10	6.0	0.4	2.0	0.2
saturated with AC-61	0	10	9	46.7	1.7	25.0	0.5	11.3	0.5	7.5	0.4	4.0	0.3	7.9	0.6	3.1	0.3	4.3	0.5	7.2	0.3	4.8	0.2	0.8	0.05	1.0	0.03	6.5	0.4	2.0	0.1
none	1,000	10	10	48.1	2.7	20.0	1.5	9.6	0.5	6.2	0.1	2.8	0.3	6.2	0.4	1.9	0.3	2.8	0.2	7.0	0.4	4.6	0.1	0.8	0.05	1.3	0.12	7.2	0.7	1.7	0.2
glue-glycerin-regular	1,000	6	7	41.5	2.7	19.2	1.2	10.2	0.6	6.6	0.2	3.7	0.2	7.1	0.6	2.5	0.2	3.3	0.3	6.1	0.4	4.1	0.2	0.8	0.06	1.1	0.08	6.9	0.4	2.1	0.1
glue-glycerin-high	1,000	10	10	35.1	2.2	14.7	0.8	9.6	0.4	6.5	0.3	4.5	0.3	9.5	0.3	2.8	0.2	3.9	0.2	5.0	0.5	3.6	0.3	0.8	0.07	1.2	0.11	6.3	0.6	1.9	0.2
saturated with AC-61	1,000	6	9	44.8	2.0	19.5	1.0	11.1	0.6	7.4	0.3	4.1	0.2	8.1	0.4	3.1	0.3	4.3	0.3	6.9	0.4	4.7	0.3	0.8	0.08	1.2	0.10	6.6	0.2	2.0	0.2

[1] $s = \sqrt{\frac{n\Sigma x^2 - (\Sigma x)^2}{n(n-1)}}$

Table 6. The Effect of Glue-Glycerin Sizing and Saturation with Acrylic Resin AC-61 on the Retention of Physical Properties of Currency Paper After Flexing.

Treatment	No. of Flexes	No. of Specimens		Elmendorf Tear g				MIT Fold Endurance 1000g-double folds				Cantilever Stiffness g-cm				Air Permeability ml/min (10cm)		Thickness				Weight per Unit Area g/m^2	Apparent Density g/cm^3			
		M	C	M	s[1]	C	s	M	s	C	s	M	s	C	s		s	M	s	C	s		M	s	C	s
none	0	10	10	102	15	120	33	2874	636	2659	541	4.4	0.7	2.3	0.3	42	2	125	2	125	3	86	.690	.03	.691	.02
glue-glycerin-regular	0	7	7	88	11	100	11	6369	1022	5124	1514	4.7	0.5	2.3	0.3	22	1	137	2	136	2	91	.663	.02	.672	.02
glue-glycerin-high	0	10	10	93	13	87	14	8265	2030	6848	1473	3.4	0.5	1.9	0.2	23	1	130	2	135	3	104	.800	.02	.769	.02
saturated with AC-61	0	10	10	92	10	110	25	4121	768	3980	1451	4.9	0.8	2.5	0.2	12	2	134	3	135	4	96	.718	.02	.717	.02
none	1,000	10	10	101	20	102	18	2770	501	2734	464	3.7	0.6	1.4	0.05	47	2	125	2	126	2	85	.679	.01	.675	.01
glue-glycerin-regular	1,000	7	7	85	6	92	14	6219	1123	4893	921	4.0	0.4	1.5	0.2	27	1	135	2	134	2	91	.671	.03	.680	.03
glue-glycerin-high	1,000	10	10	82	15	96	13	9405	2352	6529	2069	3.3	0.5	1.6	0.1	27	1	130	3	134	3	104	.801	.02	.775	.02
saturated with AC-61	1,000	10	10	92	9	106	14	3246	628	3754	962	4.3	0.3	2.0	0.1	11	2	134	3	135	4	96	.717	.02	.708	.02

[1] $s = \sqrt{\frac{n\Sigma x^2 - (\Sigma x)^2}{n(n-1)}}$

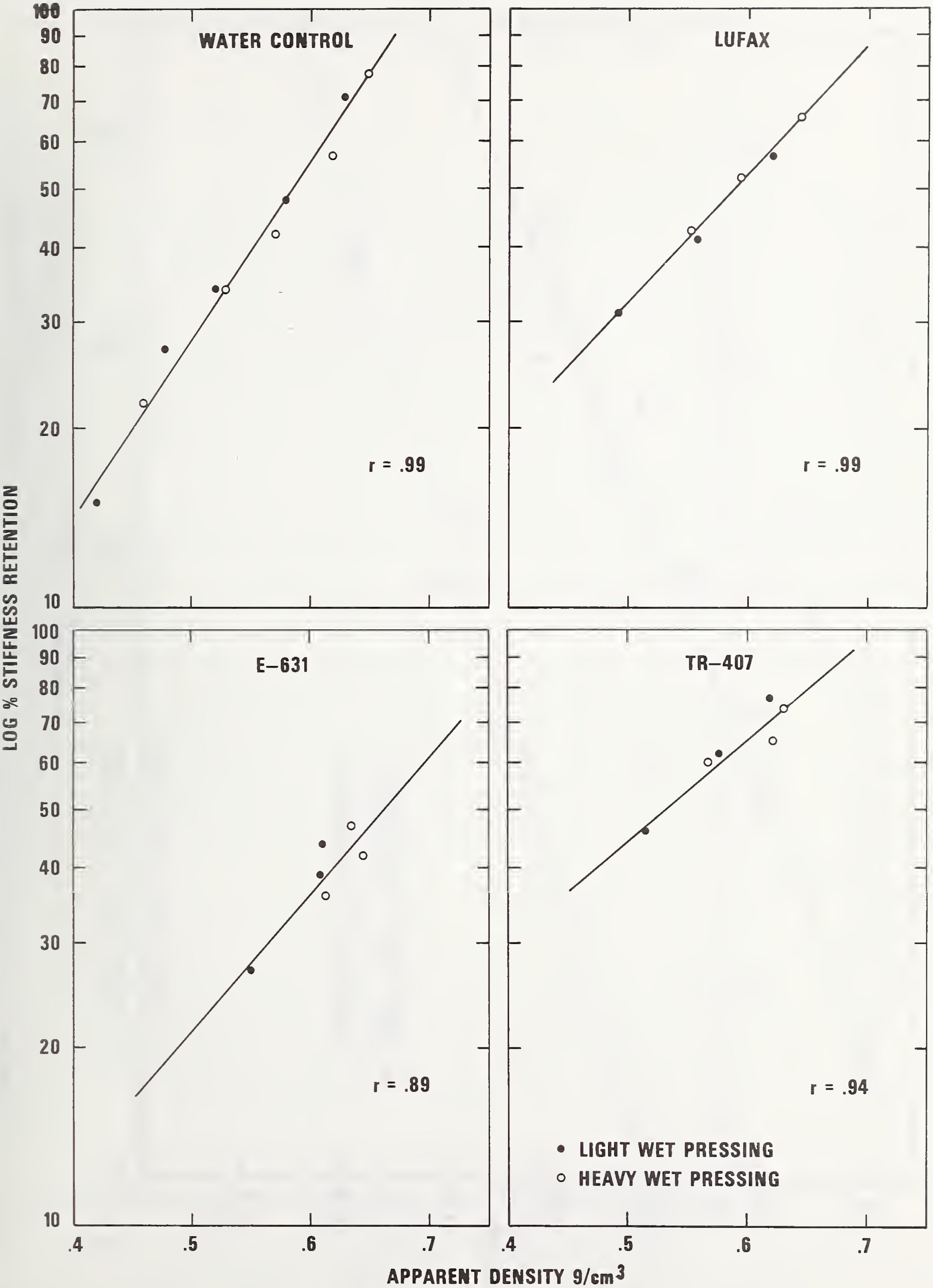

Figure 1. Relationship between apparent density and stiffness retention.

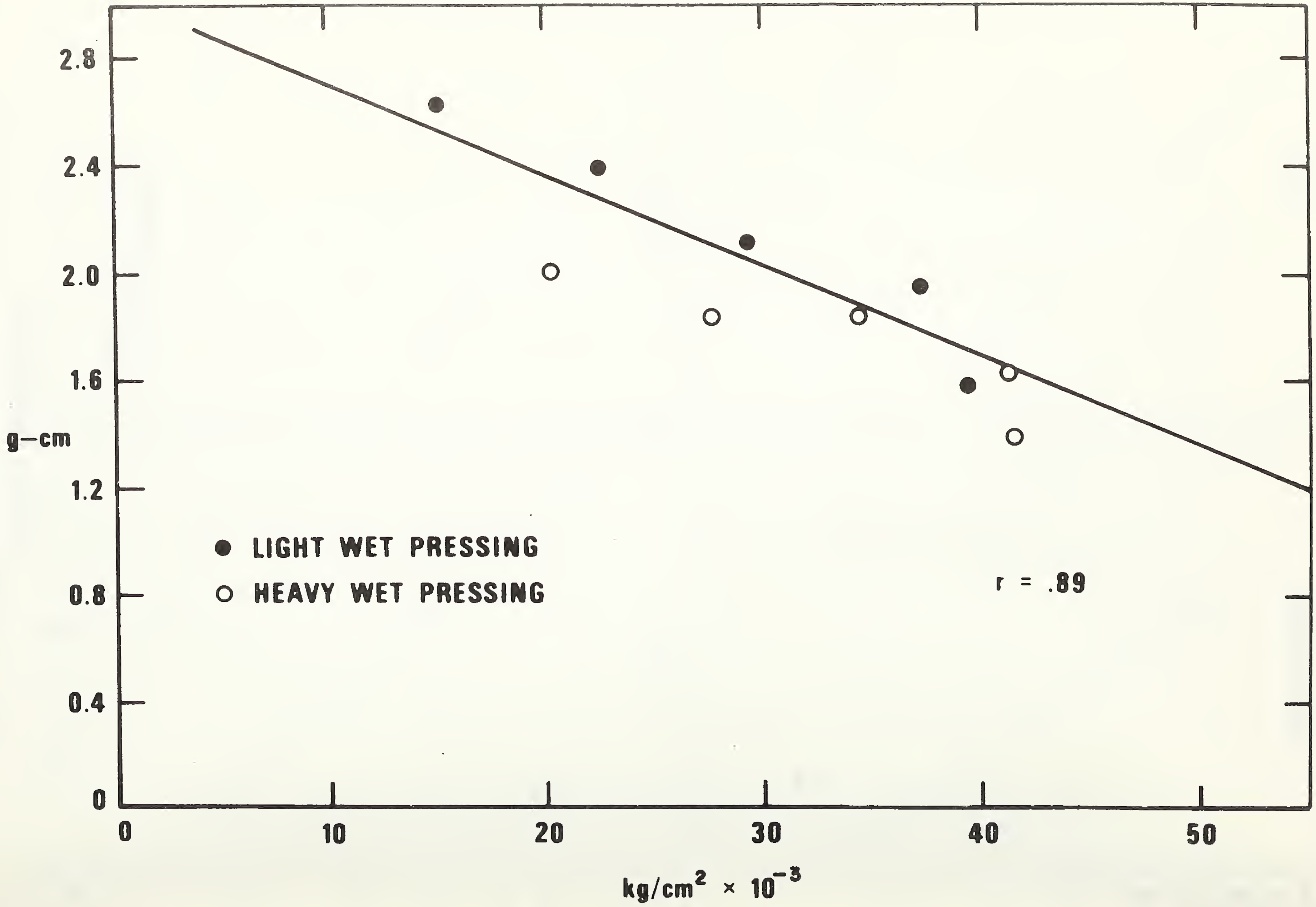

Figure 2. The relationship between modulus and bending stiffness of unflexed paper.

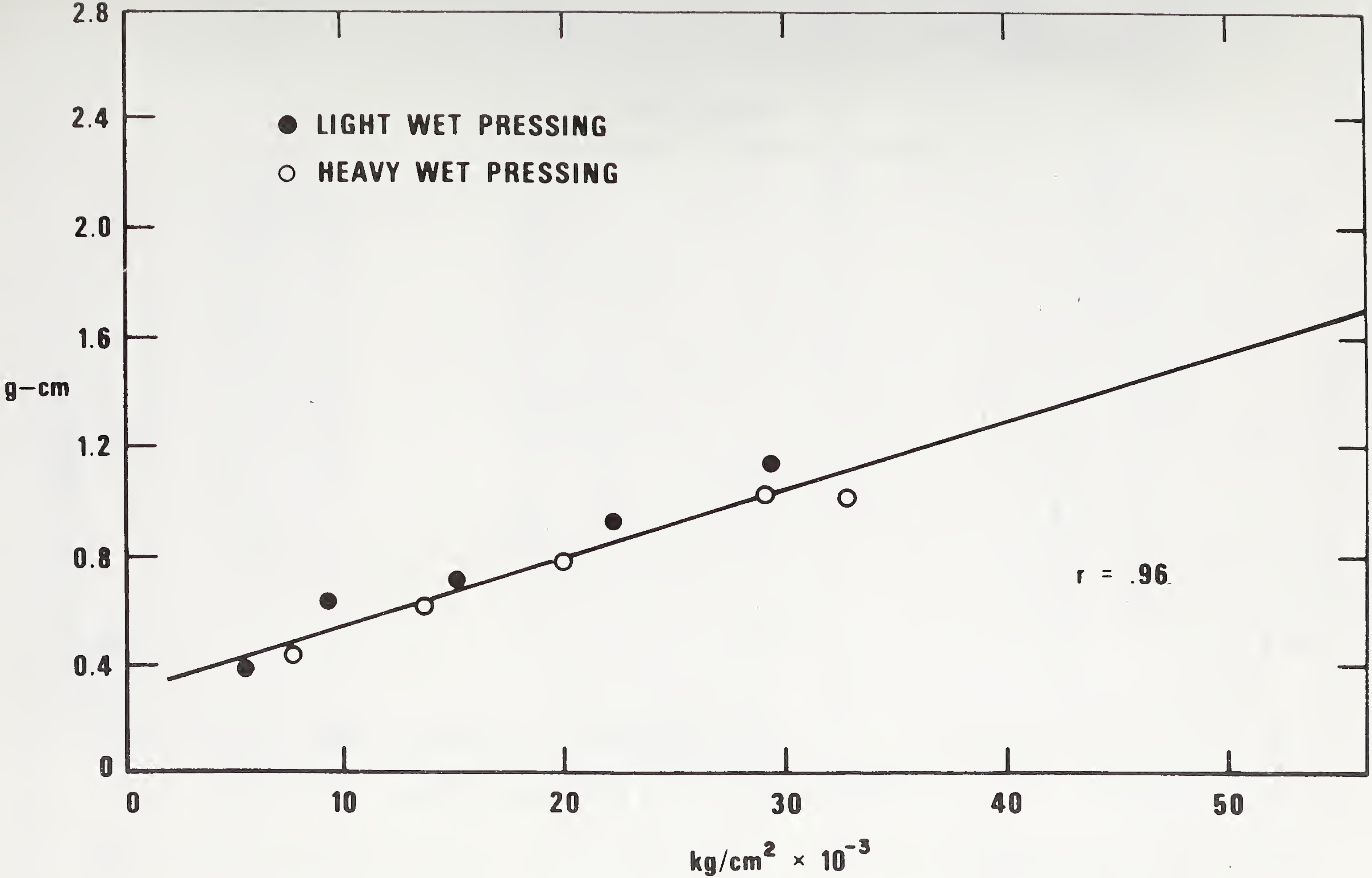

Figure 3. The relationship between modulus and bending stiffness of flexed paper.

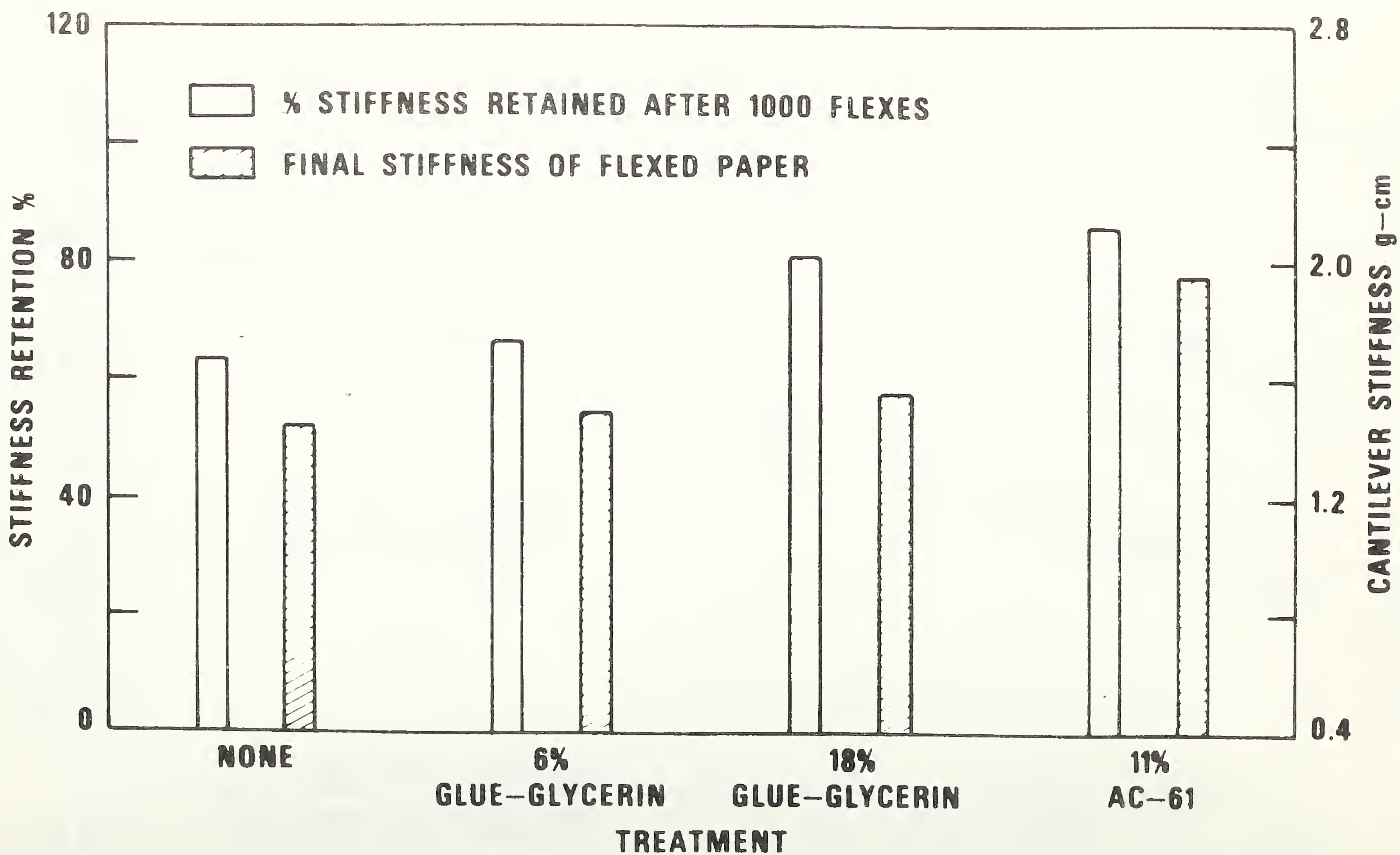

Figure 4. Retention of stiffness of currency paper after 1,000 flexes.

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The stiffness retention of paper with flexing, which is essential to the circulation life of currency, can be improved by increasing the apparent density of paper. An increase in the apparent density can best be achieved by mechanical refining (beating) of pulp, wet pressing of the formed sheet, and calendering. Additional work must be performed to determine which of the three methods is best for producing a higher density currency paper. Further improvement in stiffness retention can be achieved by modifying paper with acrylic resins by the saturation technique. Currency paper, when so modified with acrylic resin AC-61, appears to have a significantly higher stiffness retention than regular currency paper.

17. KEY WORDS *(six to twelve entries; alphabetical order, capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Acrylic resins; apparent density; calendering; mechanical refining; stiffness retention; wet pressing

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